Biased and Bias-Free Multi-Gb/s Data Links Using GaAs VCSEL's and 1300 nm SM Fiber

Peter Schnitzer and Felix Mederer

Selectively oxidized single-mode GaAs vertical-cavity surface-emitting lasers (VCSEL's) are investigated for biased 3 Gb/s and bias-free 1 Gb/s data links. Bit error rates (BER's) of better than 10^{-11} for pseudo-random data transmission over 4.3 km of standard 1300 nm single-mode fiber are demonstrated. A simple mode filter is used to suppress intermodal dispersion. The requirements of the Gigabit Ethernet are fulfilled even for bias-free operation.

1. Introduction

Optical data links are very promising in terms of their capacity to increase the speed of digital networks such as local area networks (LAN's) and wide area networks (WAN's). For continuously decreasing transmission distances high-bit-rate optical fiber links even outperform their copper-based competitors with regard to cost per available bandwidth. Due to their outstanding properties, selectively oxidized VCSEL's have become prospective candidates for transmitters in high-bit-rate fiber links. Threshold currents in the 50 μA regime [1], threshold voltages close to the bandgap voltage in combination with high wall-plug efficiencies [2], polarization control, and modulation bandwidths of 21.5 GHz [3] all show the enormous potential of these laser diodes. Multimode fiber (MMF) links of 500 m length at data rates of up to 10 Gb/s biased [4] and 2.5 Gb/s bias-free [5] have already been demonstrated. All these features in combination with geometrical advantages allowing easy formation of one- and two-dimensional arrays make VCSEL's highly attractive for various kinds of optical data links such as fiber-based [6] and free-space [7] parallel optical interconnects. Aside from few-100-m distance MMF data links, it is highly desirable to employ VCSEL's in standard 1300 nm single-mode fiber (SMF) lines in order to profit from inexpensive devices for high-bit-rate networks such as the Gigabit Ethernet which is designed for data rates of 1 Gb/s and fiber lengths of up to 550 m of 50 μm diameter MMF and $\geq$ 3 km SMF [8].
In this work, we report on laterally oxidized GaAs VCSEL's for biased 3 Gb/s and bias-free 1 Gb/s non-return-to-zero (NRZ) pseudo random bit sequence (PRBS) transmission with $2^{31}-1$ wordlength. The BER remains below 10^{-11} after transmission over 4.3 km of 1300 nm SMF and mode filtering.

2. Device structure

The laser structure under investigation was grown by solid-source molecular beam epitaxy. The bottom distributed Bragg reflector (DBR) consists of 30.5 n-type Silicon doped AlAs/ $Al_{0.2}Ga_{0.8}As$ layer pairs. The one-wavelength thick central region contains three 8 nm thick GaAs quantum wells embedded in $Al_{0.5}Ga_{0.5}As$ spacer layers to provide efficient carrier confinement. The p-type top DBR consists of 26 Carbon doped $Al_{0.2}Ga_{0.8}As/Al_{0.9}Ga_{0.1}As$ layer pairs. An extra 30 nm AlAs layer inserted in the lowest top mirror pair is selectively oxidized for current confinement after wet chemical mesa etching. In order to obtain single-mode operation the oxidation layer is shifted towards the node of the standing wave pattern yielding weak index guiding [9]. After oxidation a p-Ti/Pt/Au top ring contact is deposited on top of the mesa to achieve good ohmic contacts as well as light emission through the top DBR. Ti/Au conducting tracks and bondpads are deposited on a polyimide insulation layer. Polyimide provides a smooth planar surface, good passivation, and improves high frequency behavior due to the small permittivity. Mechanically polishing the GaAs substrate down to 150 μm and evaporating a Ge/Ni/Au broad area contact are final process steps.

3. Experiment

Fig. 1 summarizes the output characteristics of the 4 μm active diameter VCSEL source employed in the transmission experiments.

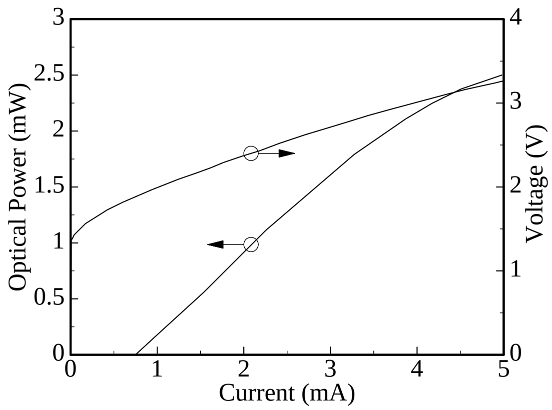

Fig. 1. Output characteristics of laterally oxidized single-mode GaAs VCSEL.

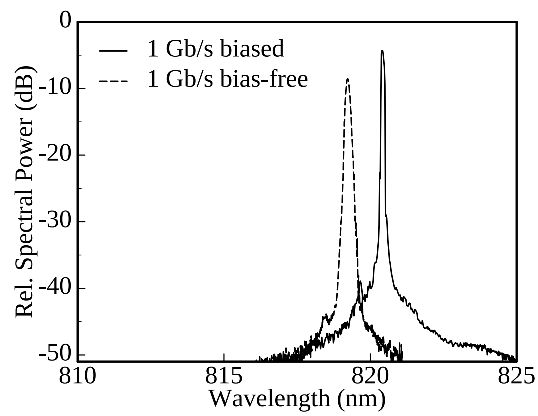

Fig. 2. Optical spectra of single-mode VCSEL with -10 dB widths of 0.15 and 0.3 nm for 2.6 mA biased $V_{pp} = 1.5$ V and bias-free $V_{pp} = 2$ V modulation, respectively.

Threshold current is as low as 750 μA and threshold voltage is 1.8 V. The laser diode shows single-mode operation up to a driving current of 5 mA. For the transmission experiments, the laser is either directly driven by a pattern generator at 1 Gb/s with $V_{pp} = 2$ V without any additional bias, or by a bias current of 2.6 mA and 1 or 3 Gb/s PRBS with $V_{pp} = 1.5$ V which are combined in a bias-tee and fed to the VCSEL source. The laser is wire bonded to an SMA socket to keep feeding lines as short as possible. Output power is launched in a butt-coupled SMF with 8.3 μm core diameter and 4.3 km length. Although butt-coupling effectively changes the output mirror reflectivity, no time-dependent feedback effects are introduced. The transmitted signal is passed through a variable attenuator and detected with a Germanium avalanche photodiode. The preamplified bit sequence is monitored with an electrical sampling oscilloscope and analyzed with a BER detector. The spectra given in Fig. 2 are centered at 819 nm and 820 nm for bias-free $V_{pp} = 2$ V operation and 2.6 mA bias current and $V_{pp} = 1.5$ V modulation, respectively. In both cases the side-mode suppression is larger than 35 dB and the -10 dB spectral width is 0.15 nm for biased and 0.3 nm for bias-free operation. Mode filtering is realized by macro bending of the fiber [10]. For a fiber subjected to small radius bends, the number of modes decreases due to the power leakage caused by radiation of higher order modes [11]. The used 8.3 μm core diameter SMF is a two-mode fiber at $\lambda = 820$ nm since we obtain

$$V = \frac{2\pi}{\lambda} a\mathrm{NA} = 3.5 \tag{1}$$

for the normalized frequency parameter [12], where $a = 4.15\ \mu$m is the core radius and NA $= 0.11$ is the numerical aperture. Step index fibers are single-mode up to $V = 2.405$ and are two-mode up to $V = 3.83$ [12]. Therefore, we observe both the LP_{01} and LP_{11} mode after 4.3 km propagation in the fiber as shown in Fig. 3 b). Simple mode filtering selects the favored LP_{01} mode displayed in Fig. 4 b).

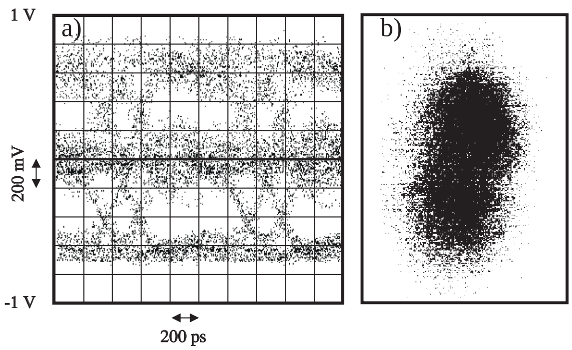

Fig. 3. Eye diagram a) and far field pattern b) of superposed LP_{01} and LP_{11} modes at 1 Gb/s PRBS with $2^{31} - 1$ wordlength recorded after 4.3 km SMF transmission without mode filter.

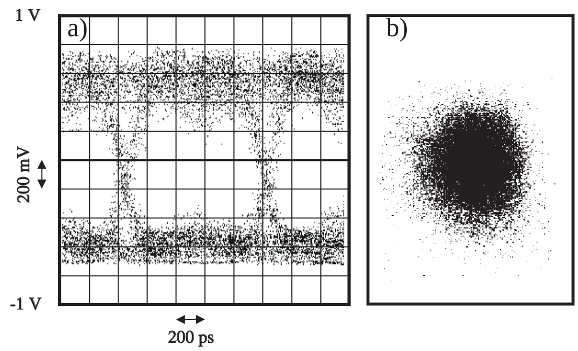

Fig. 4. Eye diagram a) and far field pattern b) of LP_{01} mode at 1 Gb/s PRBS with $2^{31} - 1$ wordlength recorded after 4.3 km SMF transmission with mode filter.

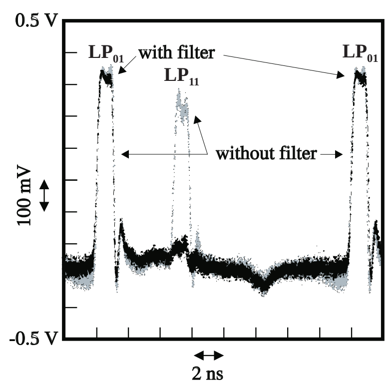

Fig. 5. Signal of LP_{01} mode (solid line) and LP_{11} mode (dashed line) after 4.3 km SMF transmission.

A fiber loop with a diameter of 17 mm and 5 windings is used for mode filtering. This diameter has been chosen to obtain sufficient losses of the LP_{11} mode. The fiber mode filter can be applied either at the fiber input or at the fiber output since no transfer of energy between the two modes is observed. Mode coupling cannot be excluded in general but depends on the micro bending spectrum of the actual fiber. The disadvantage of the coexistence of the LP_{01} and he LP_{11} modes is illustrated in the blurred eye diagram in Fig. 3 a) and the time delayed secondary pulse plotted as dashed line in Fig. 5, where the signal of a logical "one" followed by 15 logical "zeros" at 1 Gb/s after 4.3 km SMF transmission is recorded. The solid line is the information carried by the LP_{01} mode while the dashed line represents the information carried by the LP_{11} mode. Mode filtering removes the dashed line in Fig. 5 and leads to the eye diagram shown in Fig. 4 a). This eye diagram is wide-open and shows neither double lines nor any remarkable relaxation oscillations. Fig. 6 summarizes the results of the BER measurements. Solid and open circles denote 1 Gb/s biased back-to-back (BTB) testing and 4.3 km SMF transmission, solid and open squares denote 1 Gb/s bias-free back-to-back testing and 4.3 km SMF transmission, and solid and open triangles represent 3 Gb/s back-to-back testing and 4.3 km SMF transmission, respectively. The received optical powers for biased and bias-free back-to-back testing for a BER of 10^{-11} are -25.8 dBm and -24.5 dBm while the corresponding power penalties for 4.3 km SMF transmission are 2.8 dB and 2.5 dB, respectively. The on-off ratio for biased operation is about 17 dB. For biased 3 Gb/s modulation the received optical power for back-to-back testing is -22 dBm and the power penalty for 4.3 km SMF transmission is 2.1 dB.

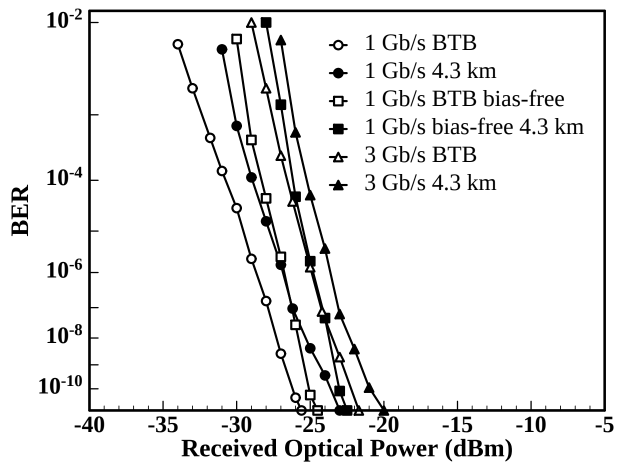

Fig. 6. Bit error rates with $2^{31}-1$ wordlength for various combinations of bit rate and modulation scheme, each for back-to-back (BTB) and 4.3 km SMF transmission.

4. Summary & Conclusion

In summary, we have demonstrated 3 Gb/s biased and 1 Gb/s bias-free $2^{31}-1$ PRBS signal data transmission with 820 nm single-mode VCSEL over an inherently two-moded standard SMF line of 4.3 km length. A BER of better than 10^{-11} has been achieved and the power penalty for 4.3 km transmission is about 2.1 dB for 3 Gb/s biased and 2.5 dB for 1 Gb/s bias-free modulation. The investigated GaAs VCSEL is able to fulfill the requirements for the Gigabit Ethernet using existing 1300 nm SMF even for bias-free operation. The single-mode VCSEL produces negligible chromatic and waveguide dispersion over the given distance due to the extremely narrow emission linewidth. However, fiber transmission produces modal dispersion which is suppressed by applying simple mode filtering and thus does not affect BER characteristics. The results show that the single-mode VCSEL's in combination with mode filtering are well suited for high-bit-rate data transmission over several kilometers distance indicating simple ways for upgrading existing fiber links for extended wavelength or bit rate operation.

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